Moon Lighting:
Illumination for Lunar Base Construction and Operations

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Abstract

Lunar bases will need lighting for exploration, construction, mining, industry, life support, operations, and maintenance. In many respects, lighting on the Moon will involve adaptations of familiar methods. Efficiency, robustness, and serviceability will be required.

During the lunar day, sunlight is available using heliostats, lenses and light tubes. Some of these items can be used for distribution of artificial light as well. Illumination may be augmented by using transparent, translucent, light-colored or reflective walls and panels.

Moon lighting presents special challenges, such as dust amelioration, heat management, and lavatube illumination. Spectrum manipulation can promote or inhibit living organisms, as desired.

Using lunar resources to manufacture lighting equipment will save money over Earth sourcing, so designs should be compatible with lunar sourced components as these become available.

Lunar Lighting Conditions

Physical Environment. On the Moon, electrical equipment must tolerate abrasive insulating dust, harsh radiation, vacuum conditions, and ambient temperature extremes from –233° to +123° C (Vaniman *et al.* 1991).

Moondust is a serious problem. Dust films on lamps and radiators reduce efficiency, lamp life and light output. Dust presents an arcing hazard and sealed fixtures may be required. Dust also attenuates light and resists current flow, perhaps enough to become a safety hazard.

During the two-week lunar day, unfiltered sunlight is available full time, without diminution by solar angle or obscuration by clouds, at 128,770 lux (lumens/m^2) (Williams and Eijadi 1992). Reflectors or windows should block wavelengths harmful to people and equipment, although sterilizing wavelengths can be useful.

Vacuum prevents convective cooling, but it allows light to travel great distances without attenuation or distortion. Inactive lamps can become extremely cold. Lamps and fixtures should be robust under temperature extremes.

Operational Environment. Initial exploration, construction, mining, industry, life support, base operations, and maintenance require well-designed lighting, strategically placed. Operations can not be expected to cease, although they may be reduced, during the two-week long lunar night, so area and operational lighting for this period are indicated. Redundant systems will be needed for reliable operation.

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TABLE 1

Levels of Illumination Approximated to Lunar Base Conditions

Earth	Low		High		Lunar
Category	ft-c	lux	ft-c	lux	Category
Aircraft Part Mfg	100	1076	100	1076	Light Manufacturing
Aircraft Hangars	100	1076	100	1076	Spaceship Hangars
Assembly, General	30	323	1000	10764	Assembly, General
Automobile Mfg	50	538	200	2153	Prefab Housing, Vehicle Ass'y
Coal Production	10	108	10	108	Lavatube Exploration, Activities
Explosives	30	323	30	323	Propellant Handling & Storage
Stone Crushing	10	108	20	215	Regolith Handling & Processing
Excavation	2	22	2	22	Regolith Mining, Base Site Excavation, Lavatube Entrance & Interior Clearing
Rock Face	50	538	50	538	Lavatube Anchors, Rilles, Crater Walls, Fault Scarps, Boring & Drilling
Iron & Steel Mfg	5	54	100	1076	Metals Mfg
Foundries	30	323	500	5382	Foundries
Chemical Works	30	323	30	323	Chemical Works, CVD Metals Processing, Solvents, Reagents, etc.
Machine Shop	50	538	1000	10764	Machine Shop
Glassworks	30	323	200	2153	Glassworks, Glass Fiber
Textile	30	323	200	2153	Fiberglas Weaving, Linen, etc.
Construction	10	108	10	108	Habitat & Base Construction
Open Yard	0.2	2	100	1076	Lavatube Shelter, Lunar Surface
Offices	20	215	200	2153	Offices
Hotels	10	108	100	1076	Habitat, Hotels
Restaurants	10	108	100	1076	Restaurants (Public Kitchens)
Library	30	323	70	753	Library, Computer Station
Schools	30	323	150	1615	Classrooms, Training, Meeting Rooms
Trolly, Coaches & Streetcars	30	323	100	1076	Mass Transit
Hospitals	30	323	2500	26910	Hospitals

Earth-based figures from Summers (1981)

Shipboard	Low		High		Lunar
Category	ft-c	lux	ft-c	lux	Category
Staterooms	5	54	15	161	Bedrooms
Baths	5	54	50	538	Baths
Passageways	5	54	5	54	Passageways
Stairs, Foyers	10	108	10	108	Stairs, Foyers
Entrances	10	108	10	108	Entrances
Lounge	10	108	10	108	Lounge
Recreation	20	215	20	215	Recreation
Dining Room	10	108	10	108	Dining Room
Library	10	108	30	323	Library, Computer Station
Enclosed Promenades	10	108	10	108	Open Base Interior Areas, Viewing Rooms
Barber Shop & Beauty Parlor	20	215	50	538	Barber Shop & Beauty Parlor
Pubs	5	54	5	54	Pubs
Swimming Pools & Gymnasiums	10	108	20	215	Exercise Rooms
Shopping Areas	20	215	20	215	Shopping Areas
Theaters	0.1	1	5	54	Theaters
Hospital	10	108	50	538	Hospital
Radio Room	10	108	10	108	Communications Office
Purser's Office	20	215	20	215	Purser's Office
Navigating Areas	5	54	50	538	Construction Office, Telerobotics Control
Service Areas	3	32	50	538	Small Business
Operating Areas	5	54	50	538	Operations, Infrastructure Maintenance, Workshops

Sport Category					Lunar Category
Playing Area	30	323	500	5382	Sports Playing Area
Audience	2	22	5	54	Audience

To shelter bases and activities, space scientists bury habitats or look to lunar lavatubes (Walden *et al.* 1998). Buried habitats or long, black basalt lavatubes are constantly dark, and light will always be necessary.

Illumination waste heat is a major problem. Lights and fixtures designed for vacuum must be able to dump waste heat. Radiators could be made on the Moon. Mirrors make effective radiators (Morea 1988), so some synergetic solutions may be possible. If a light is operated under the lunar sun, a sunshade should improve radiator performance. An active cooling system might transfer luminaire heat to a water heater. In some cases, a state-changing gel might be used (Morea 1988).

Even with efficient lights, there will be a constant tension between the amounts of illumination desired (Table 1), the costs of lighting infrastructure, and the power necessary for that illumination (Table 2). Thought must be given to what light is really necessary, how efficiently available lights can be used, and ways to use natural light and local resources as much as possible.

***In Situ* Lighting Resources.** Using *in situ* resources for illumination lowers capital and operating costs by minimizing mass lifted from Earth. Luminaires should use lunar elements such as calcium, sulfur, silicon, nickel, iron, and aluminum. Cost reduction by local production also opens a variety of markets.

TABLE 2
Luminaire Efficiencies

Type		Source	Lumens	Watts	Lumens / Watt	Life (Hours)	Lumen-Hours / Watt
Natural:	**Solar**	W&E	128,770 lux*	n/a	**n/a**	n/a	**n/a**
	Earthshine	W&E	≤13.5 lux*	n/a	**n/a**	n/a	**n/a**
Incandescents:	**Halogen Flood**	Label	630	50	**13**	2,000	**25,200**
	Krypton Flood	Label	775	60	**13**	2,000	**25,833**
	Standard Soft White	Label	840	60	**14**	1,000	**14,000**
	Standard	Label	1,190	75	**16**	750	**11,900**
	Standard Soft White	Label	1,690	100	**17**	750	**12,675**
	Halogen Flood	SYL	1,900	120	**16**	3,000	**47,500**
	SR Tungsten Halogen	LBL2	2,600	100	**26**	3,000	**78,000**
LED (est. from mlm):		SYL	384	3	**120**	20,000	**2,402,721**
Fluorescents:	**Compact**	Label	1,200	20	**60**	10,000	**600,000**
	Warm White	Label	1,500	23	**65**	15,000	**978,261**
	Space Station Spec	W&E	1,650	30	**55**	15,000	**825,000**
	F48T12DVHO 48"	SYL	3,920	115	**34**	10,000	**340,870**
	F03295048 30/CS 48"	SYL	1,530	32	**48**	20,000	**956,250**
	Fluorex	Label	4,410	42	**105**	10,000	**1,050,000**
Mercury Vapor:		Label	7,000	175	**40**	24,000	**960,000**
Sodium:	**Low-Pressure**	SYL	22,000	135	**163**	16,000	**2,607,407**
	High-Pressure	SYL	120,700	1,000	**121**	24,000	**2,896,800**
Metal Halide HID:	**Xenarc**	SYL	3,200	35	**91**	3,000	**274,286**
	250W	W&E	20,500	250	**82**	20,000	**1,640,000**
	400W	W&E	36,000	400	**90**	20,000	**1,800,000**
	1000W (est.)	W&E	110,000	1,000	**110**	20,000	**2,200,000**
	XBO 10000 W/C Proj.	SYL	500,000	9,600	**52**	500	**26,042**
Sulfur Microwave:	**Sulfur RF 100W**	LBL1, ASI	15,000	100	**150**	60,000	**9,000,000**
	1000W	LBL1, ASI	125,000	1,000	**125**	60,000	**7,500,000**
	Light Drive 1000, 5700K	Mfg	135,000	1,425	**95**	60,000	**5,684,211**
	1500W	ASI	120,000	1,500	**80**	60,000	**4,800,000**
	5900W	LBL2	450,000	5,900	**76**	50,000	**3,813,559**

Sources:
W&E: Williams and Eijadi (1992)
SYL: Sylvania http://daeitswp2.mysylvania.com/scripts/wgate/zb2cpcat/
LBL1: http://eande.lbl.gov/CBS/NEWSLETTER/NL6/S-Lamp.html
LBL2: http://eetd.lbl.gov/btd/pub/annrep94/LSals.html
ASI: http://www.neon-lighting.com/fiberOptic-intro.htm
Mfg: Fusion Lighting http://www.lightresource.com/press27.html

*Note: 1 lux = 1 lumen/square meter

“Space Candles” would produce chemical illumination using *in situ* materials. Intense light radiates from burning metallic lunar dust in lunar oxygen. Byproducts are a great deal of heat and recyclable dust-like residue. Portable space candles could light large areas without an established power grid. Earth-sourced mechanisms could be used with processed lunar metal and oxygen consumables at first. When made wholly of lunar resources, space candles’ cost benefits will be even greater.

Inside habitats, heat and environmental quality are paramount concerns. Efficient luminaires producing visible light with minimal heat and residue are desirable. Sulfur Microwave or Sulfur RF Lamps are the most efficient technology available today (Rubinstein 1995) (Table 2), and their major constituents are available on the Moon.

Porous silicon produces light at room temperature with low waste heat, and can be made by a simple electrolytic hydrogen fluoride leaching process. LEDs, or even semiconducting lasers useful for distant illumination, can be made from silicon with small amounts of suitable dopants.

Although gasses such as hydrogen, helium, neon, and argon are rare on the Moon, they may be byproducts of processes used to win high-value ^{3}He from solar wind particles implanted in lunar regolith (Haskin 1985). Only small amounts are needed for sulfur lamps, "neon" lights and gas lasers. Tritium (^{3}H), if available, can be made into lights that are self-illuminating for 15 years (Thomas 1990).

The ubiquitous presence of high-quality vacuum and the ability to achieve very cold (superconducting) temperatures may make new light sources possible. For example, electron or ion guns may power brilliant light sources.

Mirrors, light pipes, and fiber optics, made from lunar materials, can direct light from large efficient fixtures to where it's needed (Williams and Eijadi 1992). A large reflector or diffuser panel called a "light wall," either portable or permanent, would recapture otherwise wasted light.

In Table 3, scenarios, techniques, and power sources are summarized.

TABLE 3: LIGHTING SCENARIOS ON THE MOON

Scenario	Light Source	Day/Night	Powered by
Exploration and Survey	• Heliostat • Portable Light Panel, White or Foil Face • Tritium • Luminaries (Table 2): Personal, Area and Vehicle • Space Candle	D D/N D/N D/N D/N	Solar Reflected Tritium BATT Chemical
Construction	• Heliostat • Portable Light Panel, White or Foil Face • Luminaries (Table 2): Personal, Area and Vehicle • Space Candles	D D/N D/N D/N	Reflected Reflected BATT, GEN Chemical
Mining	• Luminaries (Table 2): toughened and protected • Space Candles	D/N D/N	GEN, BATT Chemical
Industry	• Large-scale Glow Walls • Luminaries (Table 2)	D/N D/N	Phosphorescence GEN
CELSS	• Heliostat • Light Pipe, Fiber Optics • Luminaries (Table 2)	D D/N D/N	Solar Reflected GEN
Operations	• Heliostat • Portable Light Panel, White or Foil Face • Light Pipe, Fiber Optics • Porous Silicon • Glow Wall • Luminaries (Table 2)	D D/N D/N D/N D/N D/N	Solar Reflected Reflected GEN Phosphorescence GEN
Maintenance	• Luminaries (Table 2): Personal, Area and Vehicle • Glow Walls	D/N D/N	BATT, GEN Phosphorescence

Abbreviations: BATT = Electric Battery GEN = Generator or Solar-charged Fuel Cells

Exploration and Survey

Rovers. Long-term exploration may include operations during lunar night, and rovers would require headlights, pointable auxiliary spotlights, small running lights, and instrument lights. Pressurized rovers will need some general interior lights. Rover lights need to be tough to survive vehicle vibrations and shocks. Lights might be needed even during lunar day to bring out details in shade. Given the glare of lunar daylight (Vaniman *et al.* 1991), these lights will need to be quite bright: mirrors might be the preferred option. However, once the entire vehicle is in shade, mirrors will not work.

Personal Lights. Individuals require personal lights. A small flashing helmet light would help identify individuals and their locations in dark surface environments (night, shade) or inside caves. This light should not be very bright, so as not to distract or interfere with other activities. A small strobe or LED, with a relatively long "off" period, should keep battery drainage minimal. A diffuser would reduce a small lamp's "annoyance" factor and improve its visibility.

Directional lights should be mounted in pairs, for redundancy and clarity, either on the spacesuit helmet or on the suit shoulders. Shoulder mounting allows a wider separation between lights, greater flexibility in aiming, and lowers lights below the gaze so illuminated targets have greater shadow relief and an improved sense of range. Suit-mounted lights allow the operator to maintain freedom to use his or her hands, although a handheld flashlight would still be required for special situations. Since suit power is limited, light efficiency is vital.

Portable Area Light. Portable area lights on telescoping stands would be useful accessories. Tritium lights might be bright enough for basic area illumination. These could do double-duty by becoming vehicle marker lights when stowed.

Heliostats. When exploration takes place during the lunar day, a Sun-tracking mirror, or heliostat, can be used to shine light into caves, crevasses, and other dark or deeply shaded areas. A heliostat would be a low-mass, low-energy, and portable way to shine light into a lavatube. Heliostats could be aimed manually or automatically to illuminate specific areas. Workers could wear individually-coded designators so that a dedicated heliostat could "follow" each one. They could then use handheld mirrors to direct light where needed in their vicinity. Light walls could be used to spread reflected sunlight over a larger area.

Construction

Surface Construction. Plans may call for most surface construction to take place during lunar day, but on occasion a job must continue even after lunar night has fallen. The transition from lunar day to night, and vice versa, while slower by far than on Earth, is much more absolute than on Earth, without an extended period of twilight. Even before nightfall or after dawn, long shadows might be a problem. Lunar construction equipment should have bright primary lights and smaller marker lights for work in dark areas. Semi-portable area lights will also be needed. In daytime, mirrors may provide some of these services, but active lights will be required at night or in large shadowed areas. As mentioned above, vehicle lights will need to be rugged and bright. They should also be offset from and slightly below operator line of sight in order to produce better object relief (Vaniman *et al.* 1991).

Lavatube Base Construction. Light level recommended for construction and other general activities is 108 – 215 lux (Table 1). This figure varies by application and environmental conditions. During the two-week lunar day, general illumination from the Sun would help lavatube base construction near any opening. Heliostats could throw light far into the cave. Mirrors could direct light even farther, around corners or curves or into specific working areas. Where this reflected light can't reach, active illumination is required. Construction and maintenance illumination may be assisted by portable light walls where otherwise light would be lost in the great void and nonreflective surface of a lavatube. Another reflection strategy would be to paint lavatube walls white, using lunar titanium dioxide (Billings *et al.* 2000).

Mining

Large-scale mining would use both area lighting and spot illumination of specific tasks. Spot lighting may be used for tasks in shadow during the two-week lunar day. Full-scale mining may continue during the night only through area lighting, at high power consumption, along with spot illumination. Regolith harvesters need to have ruggedized running lights and active illumination when run during the lunar night.

Industry

Manufacturing and other industries have specific lighting needs. For illumination both day and night, more than one lighting system could be used. Heliostats would save electricity during the day, while electric or chemical lights allow continued work over the lunar night. Light distribution systems should be designed to use both.

Controlled Ecological Life Support System (CELSS)

“Lighting requirements for plants is measured in micromole/sec m^2, which is commonly referred to as PAR, Photosynthetically Active Radiation…. Minimum illumination levels for the CELSS Module are 300 PAR (16000 lux)[;] with full sunlight desired, 2400 PAR (129000 lux).” (Williams and Eijadi 1992) The authors of the above text later state, “This [CELSS Module] is a special case because providing this level of illumination with an all-electric system would exceed the available power requirements during the initial and developmental stages of a lunar base.” The subsequent development of the exceptionally bright and efficient Sulfur Microwave Lamp (Building Technologies Program 1995) should lead to a reexamination of this possibility.

Habitats

Lighting within the habitat will necessitate different applications depending on the task (see Table 1). Special lighting may actually cleanse the air of the habitat itself. Infrared (IR) and ultraviolet (UV) can kill harmful bacteria and viruses and help sterilize the atmosphere within the habitat. Sunlight directed through certain channels could have removable filters to pass sterilizing light on demand.

Phosphorescent “glow walls” that charge up during the hours of illumination may be helpful as safety markers and “nightlights.” These panels could be used as nighttime directional, safety and emergency markers both inside and outside the habitat, on the surface or in a cave. Where available, tritium lights could perform similar services, except in areas such as habitats where people would be in their proximity for extended periods of time (Thomas 1990).

Habitat interior walls may be made of translucent lunar glass, permitting ambient light from adjacent rooms to dimly illuminate a given room. For privacy and darkness, Venetian blinds made of lunar metals could be closed.

Lunar Base Maintenance

Lunar base maintenance will require illumination, particularly during the lunar night or in a lavatube cave. Strategically placed solar-charged fuel cells could provide power to light up any exterior equipment requiring maintenance. Other illumination might be post-mounted high- or low-pressure sodium lamps with reflectors. A phosphorescent or electroluminescent glow wall could serve where bright light is not necessary. Workers would have personal lights mounted on helmets, shoulders, wrists, or handheld. Robots or rovers will probably need illumination for vision inside a lavatube or on a lunar night mission. This may be an optimized source and sensor, not necessarily using visible wavelengths. Even during lunar day, the extreme contrast between light and shadow would make lights useful for illuminating shaded areas.

Summary

Many lighting systems will be used on the Moon. During the day, reflective heliostats will save power. Where these won't reach, and during the lunar night or in lunar interiors, various electrically powered or chemical lighting systems can be used according to the application. Mass lifted from Earth is expensive, so lighting systems built from lunar *in situ* resources are preferred. Passive solar illumination of lavatubes and other features will strongly augment the detail illumination provided by electric power lighting. Industrial luminaries will require reflectors for directing light, radiators to cool lighting fixtures in vacuum, and dust amelioration. White painted lavatube walls could supplement powered luminaries in industrial areas. Electric lighting on the Moon must be robust and efficient, using such technologies as Sulfur Microwave Lamps and LEDs.

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